Comparison between EAST and ITER tokamak

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Abstract. This paper provides an overview of nuclear fusion, which is considered as an ideal energy source for the future, with emphasis on its theoretical foundation and tokamak device. In nuclear fusion, the mass of products is always less than the mass of reactants, and this “mass defect” is converted into enormous released energy. Scientists have proposed several ideas to reach such extreme conditions for nuclear fusion. Among these concepts, the tokamak device which uses magnetic fields to generate heat and confine high temperature plasma is probably the most promising one. Over the last half century, with the unremitting endeavor of building and operation a series of international tokamak projects, magnetic confinement fusion has made a lot of satisfactory successes. In this paper, two representative tokamak devices are discussed, which are International Thermonuclear Experimental Reactor (ITER) and Experimental Advanced Superconducting Tokamak (EAST), about their major difference and similarities between them. ITER is constructed with the cooperation of many countries, and it is the largest tokamak project which targets to prove nuclear fusion is commercially feasible. EAST is another tokamak device which is located in China and made great achievements of magnetic confinement nuclear fusion, such as the record-breaking plasma temperature.

Keywords: Nuclear fusion, tokamak, EAST, ITER.

1. Introduction

The development of human society is based on energy. However, the storage of traditional source of energy such as fossil fuel is limited and it has harmful impact on environment. Compared to that, nuclear fusion seems to be an ideal, clean and renewable source of energy.

However, the harsh conditions like high temperature and pressure make nuclear fusion reaction really difficulty to be brought down to earth from stars. One of the ideas to reach such extreme conditions is called Tokamak. It has a toroidal vacuum chamber and there are coils twining around it in order to create a large spiral magnetic field and intensely heat the inside plasma.

In the 1980s, tokamak experimental research made a big breakthrough. The discovery of the first high confinement discharge mode on the ASDEX facility in Germany in 1982 was a milestone [1]. In 1984, the plasma current reached 3.7 MA on the European JET device and could be maintained for several seconds.

Nowadays, a lot of tokamak projects are running, such as ITER or EAST. ITER is designed for verifying the long-time fusion energy output of tokamak and solving the most important technological problems of fusion reactors to meet the requirement of commercial reactors in the future. The aim of EAST is to build the engineering foundations for fully superconducting tokamak reactors.

Nuclear fusion still needs a lot of time to finally become perfectly controllable, since a lot of issues involving fund or material are not tackled, whereas it is the most potential source of energy in the future.

2. Overview of nuclear fusion

2.1. The principle of Nuclear Fusion

The process of two or more atomic nuclei combines and fuse together to form a new core is called “Nuclear Fusion”. There is always a “mass defect” during this process, meaning that the mass of initial materials is not preserved, and the loss of mass is converted into the form of energy and released, because according to the Einstein’s mass energy equation, $E=mc^2$, the mass of a substance is equivalent to energy. By rough calculation, 1g substance can be converted to 9000MJ energy. In laboratory, the simplest process is the fusion of two hydrogen isotopes, deuterium(D) and tritium (T) respectively, which results in the release of 17 MeV of energy splitting between the two products (a helium nucleus and a neutron). Because of the copious amount of hydrogen on earth and the inert property of helium, nuclear fusion has a great potential as a source of sustainable energy.

2.2. Nuclear Fusion in Sun

Nuclear fusion happens in every star as source of energy. It requires extremely high temperature and pressure.

The pressure and temperature in the core of Sun are high enough to make nuclear fusion happen, by which hydrogen is converted into helium and enormous energy is released. For example, two protons would combine together and emit a neutrino with low energy, and this process is considered as a primary reaction in Sun. These released neutrinos are called *pp* neutrinos and they nearly compose the whole of solar neutrino flux, dramatically outweighing those neutrinos emitted in other remaining reactions. Even though the nuclear origin of Sun’s power has been proved and the neutrino oscillation has been observed due to the detection of solar neutrinos from other secondary reactions, we still have not directly discovered neutrinos from proton-proton nuclear fusion. Whereas we have the spectral observation of *pp* neutrinos, which shows that the proton-proton fusion reaction contributes to nearly 99% of the total power of Sun, at around 3×10^{33} ergs per second.

The equation of pp cycle [2] in Sun is listed below, which shows that hydrogens fuse with each other and are converted into helium through it, resulting in the release of energy at 26.73MeV and the emitting of electron neutrinos ν_e and positrons.

$$4\mathrm{p} \rightarrow {}^{4}_{2}He + 2\mathrm{e}^{+} + 2\nu e \quad (1)$$

Surprisingly, one cubic meter of Sun can only generate 30W of heat which is even less than a normal human, and only a single proton fuses each billion years !

3. Definition of tokamak

Four concepts are proposed for controlling the thermonuclear fusion reactions. The first one is pinch, which uses the magnetic field generated by plasma itself to keep plasma in position. The second one is the magnetic mirror [3], in which high-end-density magnetic field reflects plasma to a low-end density one. Then, the third one is stellarator [4], which is a spiral system and also uses magnetic field to trap the plasma. Finally, the tokamak—a device in “doughnut “shape in which the high temperature plasma is confined by both toroidal and poloidal magnetic fields. the plasma.

In the late 1950s, the tokamak device was firstly provided in the Soviet Union. This name “tokamak” is an acronym which is made up from some Russian words, toroidalnaya kamera and manitnaya katushka, meaning a ring-shaped chamber and magnetic coil respectively. The actual meaning of tokamak is an equipment which uses magnetic field to control high temperature plasma and it has a torus configuration. Two forms of magnetic fields are involved in confining the plasma in tokamak. The first one is toroidal field (TF) which is created by external coils and the field of plsma flow. In such field, these field lines are distributed as a helical shape around the centre, which are essential for producing twisting field lines, ensuring the safe running and longevity of the plasma. The second kind of magnetic field is poloidal field, abbreviated as PF. The poloidal field is in a different direction from TF, which directs vertically upward or downward. This magnetic field is crucial for controlling the position of flow in the chamber of tokamak. The major function of the flow in plsma is to create enclosing magnetic field. Apart from that, it can also generate a vast amount of energy to heat the plasma to an immensely high temperature. Normally, a transformer coil is needed to make plasma flow in container. However, there is a technological disadvantage that it is unrealistic to ensure tokamak to run smoothly, which means tokamak doesn't have the ability to operate in a steady state or produce a continuous flow of plasma.

Nowadays, a lot of countries have their own tokamak equipment, such as the TFTR in America, JET in Europe, JT60 in Japan and EAST in China.

4. ITER project

In 1985 [5], at the Geneva Summit, former Soviet leader Gorbachev and US President Reagan proposed that the Soviet Union, the United States, Europe, and Japan jointly launch the International Thermonuclear Fusion Experimental Reactor (ITER) program. The ITER EDAA (engineering design activities agreement) defined the overall target of ITER clearly, which is "to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes".

One of the important goals of ITER is to prove that fusion energy has great potential involving environment or safety. ITER has been assessed a lot of times in order to ensure it is safe and environmentally friendly enough to be located in the territory of any country with only small changes to adapt and utilize the specific features of different sites.

The estimated total expenditure of ITER project is at nearly 3 trillion dollars. Additionally, several years after the start of running, the following cost of other things like spare parts is around 250 million dollars. However, the present investment is only fifty percent of the previous estimated cost.

ITER is designed as a long-pulse tokamak equipped with a single null poloidal divertor, and containing elongated plasma in its chamber. With the help of 50MW auxiliary heating, the nominal inductive operation has the power to generate a deuterium-tritium fusion of 500MW with a duration of 400s.

ITER is not only the largest tokamak project in scale, but also probably the most challenging scientific research so far. Undoubtfully ITER project has great necessity, and it is being undertaken world widely. A lot of countries have decided to fund its construction, enjoy the benefits it led and assume the risks of nuclear fusion together. It recruits experts from all over the world who are at the forefront of fusion or magnetic confinement research.

5. The Chinese tokamak: EAST

5.1. Introduction of EAST

The EAST (Experimental Advanced Superconducting Tokamak) project was allowed in July 1998 and started to build in 2000. It is located at the Institute of Plasma Physics of Hefei academy of Physical Science. The progress of tokamak research over the last century is the basis of its construction, and it aimed to become the vanguard of world fusion research. The construction of EAST started in March 2006, and in September 2006 [6], it successfully reached its first plasma. EAST is the first completely superconducting-shaped tokamak device in operation. It has some unique designs such as radio frequency, active water-cooled components for plasma and dominated heating system with low torque power injection. These features help the EAST become a significant machine to pave the way for ITER, the international thermonuclear experimental reactor, and other future reactors.

EAST is composed of a superconducting magnetic system, thermal shields, cryostat vessel, vacuum vessel, divertor and other in-vessel components. The main equipment of EAST is 11m high, 8m in diameter and weighs approximately 400 tonnes. Sixteen ring shaped superconducting field coils and fourteen poloidal superconducting field coils, which are made of niobium-titanium/copper cable in duct conductor, constitute the magnetic system of EAST. These magnets weigh approximately 170 tons, containing 96 tons of the TF (toroidal field) coils, 38 tons of the structure between coils, and 35 tons of the PF (poloidal field) coils. Two sets of in-vessel coils were installed to control the vertical instability of the plasma. All these technologies were developed at ASIPP with some national collaborators. Other important systems for the operation of plasma include a power supply system, vacuum and wall conditioning system, cryogenic system, heating systems and electric power drive systems, and data collection system, which were constructed at the end of 2005 and examined in 2006 before the first plasma.

Chinese scientists have carried out comprehensive experimental research on some key scientific and technological issues for future ITER 400s high-parameter operation, such as precise plasma control, safe operation of all-superconducting magnets, effective heating and driving, and interaction of plasma with wall materials, etc. Through integrated innovation, they have successfully realized a high-temperature plasma of 411s, with a central plasma density of about 2×10^{19} m^{-3}, and a high-temperature plasma with a center electron temperature greater than 20 million degrees.

At present, EAST is equipped with more than 30 MW of auxiliary heating and current drive systems and nearly 80 diagnostic systems, most of which have the capability of high-parameter steady-state operation, which can carry out cutting-edge and exploratory research on advanced fusion reactors and provide an important engineering and physical basis for fusion energy application in the early stage. EAST is a new-generation magnetic confinement fusion experimental device that has reached the international advanced level. As one of the major national scientific projects, the successful construction of EAST and its physical experiments have led China to the bleeding edge of magnetic confinement nuclear fusion research in world, and also made China as one of the significant fusion research centers in the world.

5.2. Challenges in EAST design

At present, EAST project has successfully reached 10^8 K temperature for more than one minute [7]. According to theoretical calculation, the present achieved temperature is about ten times lower [8] than actual needs.

High temperature and enough density of the receptor (H-2) are both important conditions for nuclear fusion. Since this is the case, it is difficult to satisfy both side and let the hydrogen burn calmly into helium ash, we cannot imit.

A realistic example is nuclear strategic weapon, the hydrogen bomb, which is familiar to handle and control to quite some of advanced countries early since 1951, where the spark plug, TNT explosive and the uranium-235 nuclear fuel together as three-stage lighting mode (TSLM) are successfully used. It is to say that, we have already had the ability and mature technology to ignite the hydrogen nuclear fusion by use of TSLM in explosion way. If TSML is used to nuclear fusion electrical power plant, it must be directly used to lighting up the next explosion of hydrogen nuclear fusion, like mechanism of fuel locomotives that intermittently consuming and burning chemical fuels in circles. However, no material can withstand the as high as 1 billion temperatures, so superconducting Tokamak and a good cooling technic must be used.

Furthermore, neutron irradiation is another problem. In nuclear fusion reaction, high-energy neutrons are emitted randomly and bombard the surface of equipment. These neutrons have enough kinetic energy to collide surface atoms, break their chemical bonds, cause them to be displaced and destroy the configuration of atoms. Finally, holes are built up inside the material to make it swell up and lose its original mechanical property.

6. Comparison between east and ITER

The International Thermonuclear Fusion Experimental Reactor (ITER) is the world's biggest and most complicated constructing magnetic confinement fusion device. It weighs 23000 tons and is 30 meters high, and it is located at the centre of a 180-hectare site. The members of ITER project include China, America, Japan, Korea, Russia, India and European Union, these members have nearly half of the world's populations. This project is worldwide scientific research which recruits thousands of brilliant scientists from all over the world. In general, ITER has profound political and scientific significance. The target of ITER project is to prove that nuclear fusion is scientifically feasible, demonstrate the continuous firing of plasmas, finally reach the net energy output and commercial application of fusion energy. In the next 10-year Improved Performance Stage of ITER with a tritium growth ratio at nearly 0.8 and external supply of tritium at 1.5kg/year, it is possible for ITER to achieve the goal of 1Mwa/m^2 [9]. However, because of fund-crisis, the ignition of ITER has been delayed to 2025.

By contrast, EAST has been constructed in 2000 at the Plasma Physics Institute of Chinese Academy of Sciences. EAST is the national chiefly supported project in 95 duration and whose aim is studying the fusion reactor physics and engineering technology for the steady-state operation of tokamaks, establish the programmatic and technological basis for the construction of all-superconducting tokamak reactors in the future. The Chinese EAST project has successfully procured the high temperature plasma with centre electron temperature greater than 20 million degrees for 411s. The successful construction of EAST has brought China to the forefront of world in the field of magnetic confinement fusion research. In the next ten years, the focus will be on high-level experimental research at the EAST. EAST will be upgraded with improved research capability and experimental conditions in order to carry out a large number of steady state high-performance plasma studies. This research will achieve the goal of obtaining stable and repeatable high-parameter plasma for 400s and become an international large-scale advanced test platform for providing important database to ITER.

7. Conclusion

This paper compares between the ITER project and Chinese tokamak EAST. ITER is the largest experimental fusion project in size, and its purpose is to demonstrate how net energy can be obtained from fusion reactions. Demonstrating that fusion energy can produce net electricity will be the next major step. Finally, a self-sustaining burning tokamak experimental fusion reactor will be built in order to explore in depth the physics and engineering of future commercial fusion reactors.

Compared to that, EAST is the first tokamak with completely superconducting and non-circular cross-section which is designed independently by China. It has successfully maintained a 101-second plasma at 1.2×10^8 degrees Celsius electron temperature and a high-parameter and long-pulse plasma with electron temperature of nearly 7×10^7 degrees Celsius with a duration 1056 seconds [10], which broke up the world record. The aim of EAST is to study fusion reactor physics and engineering technology for long-pulse steady-state operation of tokamaks, and promote the development of other related technologies in plasma physics.

However, there are still some problems needed to be solved in tokamak design, such as steady burning of plasma, tritium cycling and output of fusion energy. I believe in the furture, the safe, clean and efficient nuclear fusion reactor will be constructed and have both commercial and industrial applications.

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